Review of "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada"

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EXECUTIVE SUMMARY

Potential seismic hazards at Yucca Mountain affect both preclosure safety assessments and postclosure performance assessment calculations. During the preclosure period, structures, systems, and components of the geologic repository operations area must maintain radiological safety within prescribed limits both during and after an earthquake (Code of Federal Regulations, 2006, 10 CFR 63.102, 63.111, and 63.112). Seismicity is also an important input to performance assessments of the engineered barrier system for postclosure evaluations (Code of Federal Regulations, 2006, 10 CFR 63.102, 63.113, and 63.114).

The U.S. Department of Energy (DOE) conducted a probabilistic seismic hazard assessment via expert elicitation to assess the seismic hazard at Yucca Mountain (CRWMS M&O, 1998). Results included probabilistic hazard curves relating vibratory ground motion to annual exceedance probability. Extrapolation of the elicited probabilistic seismic hazard curves led to estimates of ground motions at small annual exceedance probabilities (below 10^{-6} per year) that are considered to be unrealistically large (e.g., Corradini, 2003; Kokajko, 2005; Schlueter, 2000).

In addition to concerns raised by U.S. Nuclear Regulatory Commission (NRC) staff (e.g., Kokajko, 2005; NRC, 2005, 1999; Schlueter, 2000), the 2003 Nuclear Waste Technical Review Board joint meeting on natural systems and engineered systems on seismic issues (United States Nuclear Waste Technical Review Board, 2003) focused on the very large vibratory ground motions predicted by the DOE probabilistic seismic hazard assessment at annual exceedance probabilities below 10^{-6} per year. The Nuclear Waste Technical Review Board sent a letter to DOE that expressed concern that the extrapolation of the probabilistic seismic hazard curves to very low probabilities resulted in ground motion estimates that were physically unrealistic (Corradini, 2003). The Nuclear Waste Technical Review Board noted that application of a physically unrealistic or highly conservative approach, even if acknowledged as such by DOE, could lead to a number of problems including: (i) a skewed understanding of repository behavior and the significance of different events; (ii) a consideration of events for which there is little or no understanding or engineering practice; and (iii) an undermined confidence in the scientific basis of the process under consideration (Corradini, 2003). The regulations at §63.102(j) explain that performance assessment "includes the range of credible earthquakes" in the evaluation of seismic activity.

In Technical Basis Document No. 14 (Bechtel SAIC Company, LLC, 2004a), DOE acknowledged that the large ground motions predicted by the probabilistic seismic hazard assessment at small annual exceedance probabilities (10^{-6} and below) overestimated the severity of low-probability ground motion at Yucca Mountain. To address this concern, DOE proposed to define an upper limit or cap to the level of seismic ground motion at the waste emplacement horizon (Bechtel SAIC Company, LLC, 2005). In the report titled "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada," DOE sought to define this ground motion limit in terms of a bounding horizontal peak ground velocity applicable under earthquake loads (Bechtel SAIC Company, LLC, 2005). DOE selected peak ground velocity because this is the ground motion measure that is correlated with damage to the components of the engineered barrier system in the DOE seismic consequence abstraction (Bechtel SAIC Company, LLC, 2004b). The technical basis for the DOE bounding horizontal peak ground velocity, as developed in Bechtel SAIC Company, LLC (2005), consists of four parts:

- First, the DOE postulated a strain-based failure criterion for the lithophysal rock units of the Topopah Spring Tuff. The criterion is based on the magnitude of shear strain that the rock would experience if its stress state changed from the initial *in situ* state to a damage state. The DOE referred to the shear strain, which was defined using infinitesimal strain theory (e.g., Jaeger and Cook, 1979, p. 37–42), as the "threshold shear strain" and defined the damage state in terms of a Mohr-Coulomb failure criterion (e.g., Jaeger and Cook, 1979, p. 99–101). The DOE explained that a rock body that has experienced shear strain equal to or greater than the threshold would exhibit "geologically observable damage," which the DOE defined as a physical effect of permanent deformation that would be recognizable to geologists in the field in the form of fractures, deformed or collapsed lithophysae, or slip or dilation of pre-existing fractures. Conversely, a rock body that has not experienced shear strain equal to the threshold would not contain any geologically observable damage.

- Second, the DOE estimated values of horizontal peak ground velocity necessary to generate a shear strain equal to the threshold value. Ground-motion site-response modeling results from previous one-dimensional equivalent-linear simulations (Bechtel SAIC Company, LLC, 2004c) were used to correlate shear strain and peak ground velocity, and thus to estimate the peak ground velocity needed to generate the threshold shear strain. DOE asserted that a rock that does not contain geologically observable damage could not have experienced seismic ground motion equivalent to the peak ground velocity needed to generate the threshold shear strain.

- Third, the DOE concluded that lithophysal rock of the Topopah Spring Tuff at the Yucca Mountain repository site does not show evidence of geologically observable damage, and therefore, has not experienced a seismic ground motion equivalent to the peak ground velocity needed to generate the threshold shear strain. This conclusion is based on: (i) a re-interpretation that the majority of fractures in the lithophysal rock are not of tectonic origin, but rather are related to initial cooling and lithification of the volcanic deposits; (ii) surfaces with evidence of slip are either minor or localized and do not represent widespread damage; and (iii) an interpretation that the current shapes of lithophysal cavities are evidence that the lithophysal rock has not been tectonically deformed.

- Finally, the DOE concluded that the Yucca Mountain site has not experienced horizontal peak ground velocity magnitudes equal to or greater than those associated with the DOE estimated threshold shear strain value since the deposition of the lithophysal rocks (approximately 12.8 million years ago).

The NRC requested that the Center for Nuclear Waste Regulatory Analyses (CNWRA) conduct an objective evaluation of the DOE report "Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada" (Bechtel SAIC Company, LLC, 2005). Specifically, CNWRA was to provide a comprehensive review of the technical bases used by the DOE to support the proposed bounding value for horizontal peak ground velocity, and a summary of current and ongoing research in the field of earthquake mechanics with particular emphasis on current or future research that could be used to support or refute the proposed bounding value for horizontal peak ground velocity.

CNWRA performed the review of Bechtel SAIC Company, LLC (2005) and found that although relevant geologic and engineering data and models were incorporated, a robust and objective technical basis for the proposed cap on horizontal peak ground velocity at Yucca Mountain is lacking. The conclusions reached by Bechtel SAIC Company, LLC (2005) are vulnerable to criticism both at the fundamental level of the approaches taken, and on the basis of the evidence adduced in support of the general thesis. Two analytical approaches are combined in the DOE report (Bechtel SAIC Company, LLC, 2005). The first is that the magnitude of seismic ground motion is limited by the strength of the propagating medium, and that this strength is equivalent to the shear strength at the elastic limit of the medium. The second is the use of geological observations to constrain whether the lithophysal rocks at Yucca Mountain contain a suite of structures assumed to be the result of ground motion equal to or greater than that predicted by the previous analysis.

An important premise of the DOE technical basis is the assertion that the amplitudes of ground motions are limited by the strength of the propagating medium (Bechtel SAIC Company, LLC, 2005, p. 6-1). The problem with this assertion is that the strength of a solid does not necessarily constrain the magnitudes of particle motion. The strength of a solid, defined mathematically in the form of a yield criterion, limits the magnitude of stress that can be transmitted through the material. Magnitudes of motion (e.g., particle displacement, velocity, or acceleration) are determined by the energy of the input source, boundary constraint, material stiffness, and any energy absorption associated with inelastic deformations. The yielding of a solid (i.e., when the solid is stressed to its strength limit), may cause the magnitude of motion to increase because of reduced stiffness but also may cause a decrease in motion because of energy absorption. A net increase or decrease of ground motion, therefore, may result from yielding and must be determined from case-specific analyses. A numerical experiment is described in Section 3.1.2 to illustrate potential effects of the strength of a solid on the transmission of ground motion.

The second assumption used to support the DOE technical basis is that geologically observable damage would occur pervasively in a rock mass that has experienced levels of seismic ground motion that correlate with the threshold shear strain derived from the analysis presented in Bechtel SAIC Company, LLC (2005). However, no objective or quantitative criteria are presented to distinguish between "pervasive" damage expected for seismic ground motion at or above the threshold shear strain, and weaker ground motions. Although, the DOE concluded that the absence of pervasive, geologically observable damage in the lithophysal rock units at Yucca Mountain implies that seismic ground motion large enough to cause such damage has not occurred, it should be noted that dozens of faults and tens of thousands of fractures of cooling and tectonic origin have been measured in the volcanic strata mapped at Yucca Mountain. Criteria for recognizing pervasive or widespread, geologically observable damage that might result from seismically induced ground motion are not established in Bechtel SAIC Company, LLC (2005). Geological data available for the Yucca Mountain site are not sufficiently analyzed in Bechtel SAIC Company, LLC (2005) to justify the conclusion that ground motions have not exceeded the estimated threshold value during the last 12.8 million years.

The staff evaluation identified several concerns regarding the assertion that Yucca Mountain does not exhibit evidence of widespread, geologically observable damage and the analyses used to establish a technical basis for the proposed cap on horizontal peak ground velocity:

- Geologic deformation is spatially heterogeneous (i.e., localized). Once a geologic structure (e.g., a fault or fracture) forms, subsequent deformation is accommodated most efficiently along the pre-existing structure rather than through the formation of a new structure. This is especially true for faults and fractures because the energy necessary to slip along an existing fault or fracture surface is generally less than the energy necessary to form a new fault or fracture surface. This is exemplified by the relatively narrow fault zones at Yucca Mountain that have accommodated large displacements over millions of years between relatively broad fault blocks. Consequently, large seismic ground motions may have occurred at Yucca Mountain in the past with much of the motion and strains accommodated by slip and opening or closing of existing structures such that little or no damage of the rock bounded by these structures occurred. Geologic deformation is also scale dependent. Structural analysis at the scale of the entire repository footprint may reveal a few large faults, whereas structural analysis at the scale of an outcrop or drift would reveal numerous small faults and fractures. The DOE analysis is based on spatially and stratigraphically distributed samples from Yucca Mountain, but does not adequately utilize the wealth of available fault and fracture data.

- The threshold shear strain, as defined in Bechtel SAIC Company, LLC (2005), lacks a rigorous technical basis. There are two concerns with the information that DOE used to determine the threshold shear strain: (i) the threshold shear strain values are based entirely on calculated information, and measured strain data for lithophysal rock available to DOE were not included; and (ii) important rock-deformational processes that can affect the threshold shear strain were not accounted for in the numerical models that DOE used for its calculations. These concerns are discussed in more detail in Section 3.3.1.

- The approach of using one-dimensional equivalent-linear site-response analyses to derive the shear strain magnitudes as a function of horizontal peak ground velocity provides limited support for a credible ground motion bound. The equivalent-linear method has been used to approximate the nonlinear response of soils to a seismic excitation, but it cannot be used to model permanent displacements because the shear strains return to zero after loading is complete. The equivalent-linear method may not be appropriate for simulating the high strains and strong ground motions that are associated with low probability seismic events at the Yucca Mountain site. Furthermore, the one-dimensional model cannot account for important two- and three-dimensional effects (e.g., effects of topography, and faulted or dipping layers). In addition, the dynamic material property value used for the one-dimensional equivalent-linear analyses is based on experimental data that were collected under conditions that are not representative of low probability seismic events at the waste emplacement level at Yucca Mountain. These concerns are discussed in more detail in Section 3.3.2.

- Evidence presented by the DOE to support their conclusion that the lithophysal tuff at Yucca Mountain does not exhibit geologically observable damage is non-quantitative and inconclusive. The wide range of literature that has been published on the tectonic history of the Yucca Mountain region during the past two decades documents clearly that geologic structures reflecting tectonic deformation are present at Yucca Mountain and that many of these structures remain tectonically active (e.g., Simonds, et al., 1995; Stepp, et al., 2001). The reclassification of the majority of fractures at Yucca Mountain as "cooling-related" is not convincingly supported. Furthermore, early formation of

fractures may favor fracture reactivation (i.e., slip, opening, closing) over the generation of new fractures during seismic ground motion, thus suppressing generation of new tectonic joints (e.g., Davatzes, et al., 2005; Ferrill, et al., 1999, 1998; Morris, et al., 1996). Additionally, the use of lithophysae shape as a strain marker is not an accepted strain analysis technique in the structural geology community. Rigorous strain analysis requires that strain markers have predictable geometric characteristics (e.g., a known initial shape or symmetry) so that comparison of undeformed and deformed shapes can be performed (cf., Ramsay, 1967). There is no evidence presented by the DOE that lithophysae meet such criteria. These concerns are discussed in more detail in Section 3.3.3.

In summary, the authors have significant concerns with the technical bases used by the DOE to support its proposed cap on horizontal peak ground velocity at Yucca Mountain (Bechtel SAIC Company, LLC, 2005). It should be noted that the authors only evaluated the scientific and engineering characteristics of the technical bases used by the DOE. Staff did not assess whether the proposed bounding value for horizontal peak ground velocity is appropriate.

Since 2004, several DOE-sponsored workshops on extreme ground motions have taken place; in response to NRC requests, the authors also reviewed material from these workshops in order to develop suggestions for possible paths forward. The most recent workshop was held in August 2005 and dealt primarily with defining physical limits to ground motion at Yucca Mountain. The workshop objective was to develop a four-year work-plan in research areas that include nonlinear wave propagation modeling, dynamic rupture modeling, fault zone geology research, and laboratory rock mechanics experiments. Future attempts at defining an upper bound to horizontal peak ground velocity that are directed at studies of the mechanics of earthquake processes such as those developed at the 2005 workshop could add physical realism and may overcome current limitations in the DOE approach for assessing peak ground velocities for Yucca Mountain. Because the original DOE seismic hazard analysis was developed through an expert elicitation process, DOE also could update the elicitation to consider new information relevant to understanding the physical processes associated with large motion, low probability earthquakes in the vicinity of Yucca Mountain, Nevada.

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ACKNOWLEDGMENTS

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Data used to support conclusions in this report are taken from documents published by the U.S. Department of Energy contractors and supporting organizations; the respective sources of these non-CNWRA data should be consulted for determining the level of quality assurance.

ANALYSES AND CODES: ABAQUS[®] Version 6.5-6 (Hibbitt, Karlsson & Sorenson, Inc., 2005) was used to examine the effects of a thin weak layer on ground motion. Analyses presented in this report are documented in Scientific Notebook Number 789E.

References:

Hibbitt, Karlsson, and Sorensen, Inc. "ABAQUS." Version 6.5-6. Pawtucket, Rhode Island: Hibbitt, Karlsson, and Sorensen, Inc. 2005.

1 INTRODUCTION

1.1   Purpose

The potential high-level waste repository site at Yucca Mountain, Nevada, is located in a seismically active region of the United States. Both preclosure seismic safety assessments, and postclosure performance assessment calculations may be affected by consideration of the effects of earthquakes. During the preclosure period, structures, systems, and components of the geologic repository operations area must maintain radiological safety within prescribed limits during and after an earthquake (Code of Federal Regulations, 2006, 10 CFR 63.102, 63.111, and 63.112). For postclosure evaluations, seismicity is an important input to the performance assessment of the engineered barrier system (Code of Federal Regulations, 2006, 10 CFR 63.102, 63.113, and 63.114).

To assess the seismic hazard at Yucca Mountain, the U.S. Department of Energy (DOE) conducted a probabilistic seismic hazard assessment via expert elicitation (CRWMS M&O, 1998). The probabilistic seismic hazard assessment provided ground motion levels as a function of annual exceedance probability for a hypothetical reference rock outcrop, referred to as Point A in Figure 1-1. The DOE then performed site response modeling (Bechtel SAIC Company, LLC, 2004c) in order to develop site-specific hazard curves for the repository emplacement level (Point B in Figure 1-1), and the surface facilities area (Points D and E in Figure 1-1). The probabilistic seismic hazard assessment methodology, including the use of expert elicitation, has been used to support design, construction, and licensing of nuclear facilities [e.g., the Consolidated Safety Evaluation Report Concerning the Private Fuel Storage Facility, (NRC, 2002)]. The performance assessment for Yucca Mountain needs to consider low annual exceedance probabilities. In particular, the regulations at §63.102(j) explain that performance assessment "includes the range of credible earthquakes" in the evaluation of seismic activity.

When extrapolated to small annual exceedance probabilities (below approximately 10^{-6} per year), the probabilistic seismic hazard assessment, and consequently the site-specific hazard curves for the potential repository, resulted in predictions of ground motion levels that to many scientists and engineers appear unrealistically large. Concerns regarding unrealistically large ground motions for low probability seismic events were expressed by both the U.S. Nuclear Regulatory Commission (NRC) (e.g., Kokajko, 2005) and the Nuclear Waste Technical Review Board (Corradini, 2003). The DOE recognized that the probabilistic seismic hazard assessment yields predictions of ground motion at annual exceedance probabilities less than 10^{-6} per year that are unrealistically large (Bechtel SAIC Company, LLC, 2004a). For this reason, the DOE developed an approach to bound the low probability tail of the hazard curve for horizontal peak ground velocity at the potential repository waste emplacement level (Bechtel SAIC Company, LLC, 2005). The ground motion bound was based on interpretations of rock-test data, geologic observations, two-dimensional numerical models, and one-dimensional ground-motion site-response modeling.

Point C

Point E   Point D

Tuff

Alluvium/
Colluvium

~330 m (213 to 457 m)   Tuff
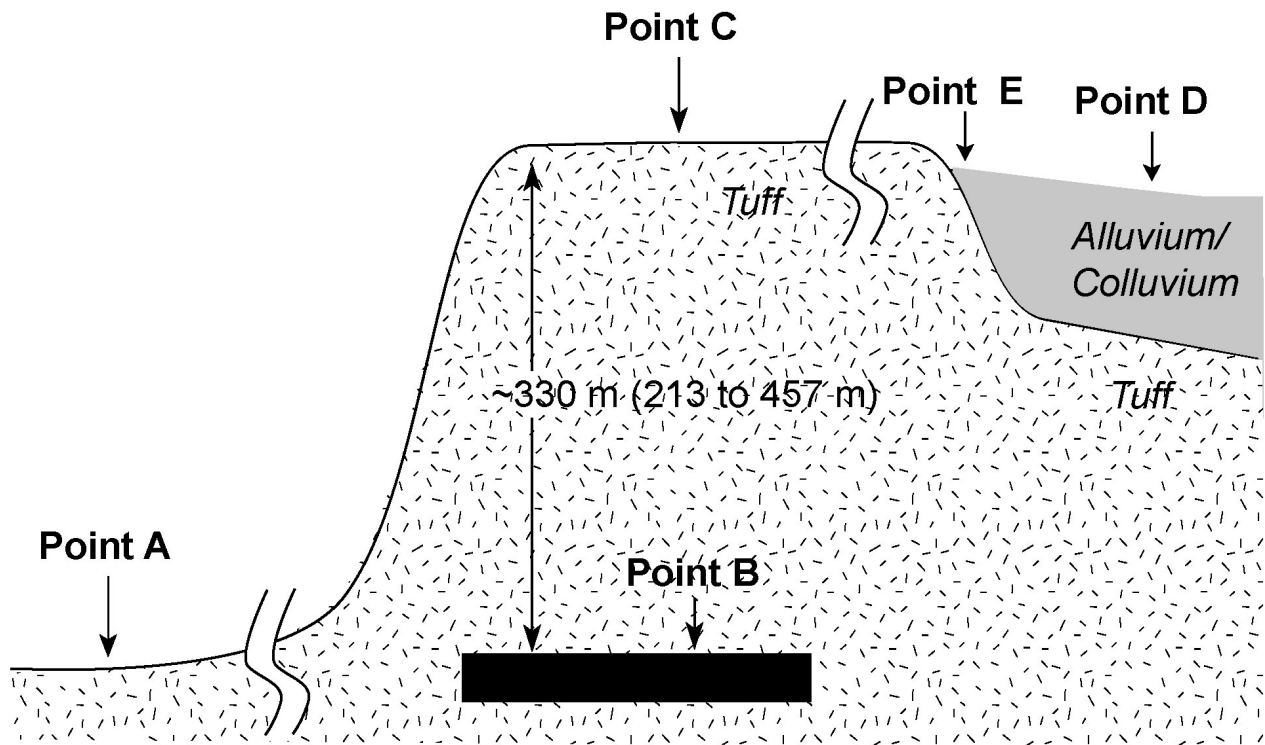
Point A

Point B

Figure not to scale

LEGEND

Point A - Reference rock outcrop used in PSHA

Point B - Rock site in waste emplacement level

Point C - Rock site above waste emplacement level

Point D - Soil site at surface facilities area

Point E - Shallow soil/rock at surface facilities area

**Figure 1-1. Schematic Cross-Section Profile Across the Yucca Mountain Site Showing the
Relative Locations of Points A, B, C, D, and E
(Modified From Bechtel SAIC Company, LLC., 2004c)**

This report provides an evaluation of the theory, data, and analyses used in the report Peak Ground Velocities for Seismic Events at Yucca Mountain, Nevada (Bechtel SAIC Company, LLC, 2005) to develop a bounded hazard curve for horizontal peak ground velocity at the potential repository emplacement level. The purpose of this report is to review the data and analyses presented in Bechtel SAIC Company, LLC (2005) that support a bounded hazard curve for horizontal peak ground velocity. Specifically, this report provides the NRC staff with the necessary technical bases to support issue resolution with the DOE during the prelicensing period. The goal of issue resolution during this prelicensing period is to ensure that the DOE has assembled sufficient information for the NRC staff to conduct a license application review.

1.2   Scope

This report provides a summary (Chapter 2) and objective evaluation (Chapter 3) of the DOE technical bases, as presented in Bechtel SAIC Company, LLC (2005), used to support the proposed bounding value for horizontal peak ground velocity. This report also provides a summary of some current research in the field of earthquake mechanics (Chapter 4) with emphasis on current or future research that could be used to support or refute the proposed bounding value for horizontal peak ground velocity. The report is organized as follows.

Chapter 2 summarizes the DOE data and analyses, as presented in Bechtel SAIC Company, LLC (2005), used to support the proposed bounding value for horizontal peak ground velocity

- Section 2.1 focuses on the DOE analysis to determine the threshold shear strain required to cause geologically observable damage in the lithophysal rock units of the Topopah Spring Tuff.

- Section 2.2 discusses the DOE evaluation of geologic data used to infer that seismically induced geologically observable damage is not present in the lithophysal rock units of the Topopah Spring Tuff.

- Section 2.3 focuses on the DOE use of previous results of ground-motion site-response modeling (Bechtel SAIC Company, LLC, 2004c) to determine the level of shear strain that is associated with various levels of horizontal peak ground velocity. This section also describes the methodology used by the DOE to develop a bounded hazard curve for horizontal peak ground velocity at the potential repository waste emplacement level.

Chapter 3 contains the review of the technical bases used to support the proposed bounding value for horizontal peak ground velocity, as developed in Bechtel SAIC Company, LLC (2005)

- Section 3.1 focuses on the authors' concerns regarding the DOE assumption that the amplitude of ground motion is limited by the strength of the propagating medium. While the strength or yield criterion of a solid limits the magnitude of stress that can be transmitted through a material, it does not necessarily limit the particle motions even if the stress limit is reached. The results of an independent Center for Nuclear Waste Regulatory Analyses (CNWRA) analysis are used to examine the effects of material strength on the transmission of ground motions and to evaluate the DOE assumption that the amplitude of ground motion is limited by the strength of the transmitting medium.

- Section 3.2 focuses on the authors' concerns regarding the DOE assumption that geologically observable damage would occur pervasively in a rock mass that has been exposed to extreme ground motion. The authors express concerns that the criteria for recognizing pervasive or widespread geologically observable damage that might result from seismically induced ground motion are not established in Bechtel SAIC Company, LLC (2005). In addition, geological data available for the Yucca Mountain site are not sufficiently analyzed in Bechtel SAIC Company, LLC (2005) to justify the conclusion that ground motions have not exceeded the estimated threshold value during the last 12.8 million years.

- Section 3.3 focuses on additional concerns regarding the technical bases used by the DOE in Bechtel SAIC Company, LLC (2005) to support the proposed bounding value for horizontal peak ground velocity. These additional concerns include

  — The information used by the DOE to develop an estimate of the threshold shear strain value is insufficient.

  — The results from one-dimensional equivalent-linear site response analyses to derive the shear strain magnitude as a function of horizontal peak ground velocity do not support the correlation of these two parameters.

  — The evidence presented by the DOE to support the conclusion that the lithophysal rock at Yucca Mountain does not exhibit geologically observable damage is not technically defensible.

Chapter 4 provides a discussion of ongoing research efforts that may contribute to the development of credible ground motion bounds. This ongoing research is being performed by researchers from the Southern California Earthquake Center, the U.S. Geological Survey, and Pacific Earthquake Engineering Research Center, and is funded by the Science and Technology Program of the Office of Civilian Radioactive Waste Management of the DOE.

Chapter 5 provides a summary of the conclusions regarding the DOE technical basis for the proposed bounding value of horizontal peak ground velocity, as well as discussion of potential paths forward toward the development of a credible range of ground motions for low probability seismic events.

2 SUMMARY OF THE DOE METHODOLOGY

The technical basis for the DOE bounding horizontal peak ground velocity, as developed in Bechtel SAIC Company, LLC (2005), consists of four parts. First, DOE calculated the magnitude of shear strain (referred to as the threshold shear strain) necessary to cause geologically observable damage in the lithophysal rock units of the Topopah Spring Tuff. Second, the DOE estimated values of horizontal peak ground velocity necessary to generate a shear strain equal to the threshold value. Third, the DOE concluded that lithophysal rocks of the Topopah Spring Tuff at the Yucca Mountain repository site do not show evidence of geologically observable damage, and, therefore, have not experienced seismic ground motion equivalent to the peak ground velocity needed to generate the threshold shear strain. Fourth, the DOE concluded that the Yucca Mountain site has not experienced horizontal peak ground velocity magnitudes equal to or greater than those associated with the DOE threshold shear strain value since the deposition of the lithophysal rocks (approximately 12.8 million years ago).

2.1. Calculation of Threshold Shear Strain Needed to Cause Geologically Observable Damage in Lithophysal Rock Units of the Topopah Spring Tuff

DOE postulated a strain-based failure criterion for the lithophysal rock units of the Topopah Spring Tuff. The criterion is based on the magnitude of shear strain that the rock would experience if its stress state changed from the initial *in situ* state to a damage state. DOE referred to the shear strain, which was defined using infinitesimal strain theory (e.g., Jaeger and Cook, 1979, pp. 37–42), as the "threshold shear strain" and defined the damage state in terms of the Mohr-Coulomb failure criterion (e.g., Jaeger and Cook, 1979, pp. 99–101). DOE explained that a rock body that has experienced shear strain equal to or greater than the threshold would contain "geologically observable damage." DOE defined geologically observable damage as a physical effect of permanent deformation that would be recognizable to geologists in the field in the form of fractures, deformed or collapsed lithophysae, or slip or dilation of pre-existing fractures. Conversely, a rock body that has not experienced shear strain equal to the threshold would not contain any geologically observable damage. DOE calculated the threshold shear strain using calculations based on (i) linear elasticity and the Mohr-Coulomb yield criterion using the results of unconfined compression testing of lithophysal rock, and (ii) numerically simulated testing of lithophysal rock specimens using computer codes PFC2D and UDEC, developed by Itasca Consulting Group (Bechtel SAIC Company, LLC, 2005, p. 6-10).

2.1.1 Calculation of Threshold Shear Strain Based on Linear Elasticity and the Mohr-Coulomb Yield Criterion

This approach consists of using stress-strain relationships based on linear elasticity to calculate the shear strain associated with a change in stress from the initial state to a damage state (Bechtel SAIC Company, LLC, 2005, p. B–10). DOE performed the calculation using values of Young's modulus and unconfined compressive strength obtained from laboratory compression testing of large-diameter cylindrical specimens of lithophysal rock from the Topopah Spring Tuff. The damage state was determined based on the Mohr-Coulomb yield criterion using the unconfined compressive strength and an estimated friction angle. Values for other parameters needed for the calculation (e.g., Poisson's ratio and *in situ* horizontal stress) were assumed or

estimated from other data. Measured strains from the laboratory testing were not used, except for the calculation of Young's modulus.

2.1.2 Calculation of Threshold Shear Strain Based on Micromechanical Modeling of Lithophysal Rock

The DOE information also includes results from numerically simulated compression testing of lithophysal rock specimens, performed using PFC2D and UDEC computer codes (Bechtel SAIC Company, LLC, 2005, p. 6-10). Lithophysal rock was modeled as an assemblage of bonded particles with a distribution of void spaces representing lithophysal openings. Disk-shaped particles were used in PFC2D and polygonal particles in UDEC. Values of micromechanical parameters needed for the models were evaluated by calibrating the elastic stiffness and compressive strength of the model assemblage against the elastic stiffness and unconfined compressive strength of the rock determined from laboratory testing. Several model calculations were performed to determine the effects of lithophysal porosity and lithophysae shape on the calculated mechanical behavior. The shear strain experienced by the simulated rock specimen by changing its stress state from an initial state to a damage state was calculated. Two initial stress states corresponding to specimen depths of 250 and 400 m [820 and 1,312 ft], and two damage states corresponding to the peak strength state and the onset of volumetric expansion, were used in the calculations.

2.1.3 Threshold Shear Strain Results

The results of the two sets of calculations as interpreted by DOE are summarized in Bechtel SAIC Company, LLC (2005, Figures 6-5 to 6-7). DOE indicates the value of threshold shear strain for lithophysal rock likely lies in the range of 0.09–0.25 percent based on the two sets of calculations. A probability density function describing the calculated information is provided in Bechtel SAIC Company, LLC (2005, p. 6-18, Figure 6-7).

2.2 DOE Evaluation of Geologic Data

Section 6.3 and Appendix A of Bechtel SAIC Company, LLC (2005) outline the methodology used to assess whether the lithophysal rocks of the Topopah Spring Tuff at Yucca Mountain show evidence of geologically observable damage that would be expected from extreme seismic shaking (i.e., shaking associated with low probability earthquakes). The observations and analyses focus on two geologic features—fractures and lithophysae. The analyses are based primarily on data collected in the Exploratory Studies Facility and the Enhanced Characterization of the Repository Block Cross-Drift, although some data from surface- and subsurface-based boreholes are also used to assess fracture characteristics.

The assumption made by the DOE is that extreme seismic shaking would result in geologically observable damage in the rock mass that is pervasive or widespread at the scale of the repository (Bechtel SAIC Company, LLC, 2005). Geologically observable damage is also referred to in the report as mechanical damage and catastrophic damage. Damage here refers to structures developed within the rock, such as faults and fractures, and does not refer to the response of engineered features, such as buildings or tunnels. Geologically observable damage is described by the DOE as a physical effect of permanent deformation that would be recognizable by field geologists as the formation of new fractures, slip or dilation of pre-existing fractures, or deformed or collapsed lithophysae (Bechtel SAIC Company, LLC, 2005).

2.2.1 Fracture Petrogenesis

The petrogenesis or geologic history of the fractures in the Topopah Spring Tuff was examined in terms of the timing of formation with respect to the deposition and cooling of the volcanic material that formed the tuff. In contrast to previous investigations, this examination focused specifically on the mineral and textural relations and did not evaluate geometric characteristics such as orientation, planarity, or terminations (Bechtel SAIC Company, LLC, 2005, Appendix A). The fracture analyses were separated into two phases.

The first phase examined fractures on slabs from cores collected from two surface-based boreholes and 32 subsurface-based boreholes. Fractures were categorized into one of two classes using an approach similar to that used by Buesch, et al. (1999). Fractures displaying either vapor-phase mineral coatings or rims were classified as cooling-related and inferred to have formed within 100 years of deposition of the volcanic material. Fractures that lack either vapor-phase mineral coatings or rims were classified as indeterminate (i.e., timing of formation is not constrained).

The second phase re-examined detailed line survey data collected in the Enhanced Characterization of the Repository Block Cross-Drift as part of the overall site characterization activities conducted at Yucca Mountain (Mongano, et al., 1999). Detailed line survey data collected in the Exploratory Studies Facility (Albin, et al.,1997; Barr, et al., 1996; Beason, et al., 1996; Eatman, et al., 1997) were not analyzed during this phase. The detailed line survey data include observations of both large-scale fractures {i.e., trace lengths $\geq$1 m [$\geq$3.3 ft]} as well as small-scale fractures {i.e., trace lengths $\leq$1 m [$\leq$3.3 ft]}. Although the detailed line survey data were collected primarily for analysis of geometric relationships (e.g., orientation, spacing, trace length), the original data set does include some information on features such as fracture filling or coatings on fracture walls. Fracture definitions in the original detailed line survey data are as follows: (i) *faults* or *fault zones* are discontinuities with $\geq$10 cm [$\geq$3.9 in] offset; (ii) *shears* or *shear zones* are discontinuities with $\leq$10 cm [$\leq$3.9 in] offset or indeterminate offset; (iii) *vapor phase partings* are discontinuities that consist of roughly linear accumulations of vapor-phase minerals (as seen on tunnel walls) and are sub-parallel to lithostratigraphic layering; (iv) *cooling joints* are planar discontinuities with long trace length; and (v) *fractures* are discontinuities that lack other characteristics, including observable offset.

The re-examination of the detailed line survey data provided the basis for the reclassification of fracture petrogenesis (Bechtel SAIC Company, LLC, 2005). Along with the originally recognized cooling joints and vapor phase partings, additional cooling-related fractures were identified on the basis of one or more characteristics that included vapor-phase mineral coatings, rims, and tubular structures or tubes. A new fracture hierarchy was defined in Bechtel SAIC Company, LLC (2005) with three groups of cooling-related fractures: (i) Type 1 fractures have either rims or tubular structures; (ii) Type 1+ fractures were originally classified as cooling joints or vapor phase partings; and (iii) Type 2 fractures display the presence of any vapor phase mineral coating.   Any fracture not meeting the criteria for Types 1, 1+, or 2 was assigned to the indeterminate group.

The application of the reclassification criteria is documented in two Excel spreadsheets *(PGV ECRB DLS Frac-Fill.xls* for the large-scale fractures and *PGV SSF DLS Frac-Fill.xls* for the small-scale fractures) included as part of Appendix D (Bechtel SAIC Company, LLC, 2005).

Table 2-1 summarizes the results of the DOE fracture petrogenesis analyses. Results for the fractures observed in the core slabs and the large-scale fractures measured by the detailed line survey are consistent with approximately 70 percent of the fractures assigned to the cooling-related category. The remainder are classified as indeterminate, although DOE suggests that these fractures could be the product of late-stage cooling. Results for the small-scale fractures measured by the detailed line survey technique show that slightly less than 50 percent of the fractures fall into the cooling-related category. The DOE further state that the vast majority of the fractures, regardless whether observed in core slabs or measured by detailed line survey, have no evidence for shear or mechanical degradation (Bechtel SAIC Company, LLC, 2005). However, the DOE acknowledges that fractures that contain broken or crushed rock, or sand (318 out of 1,810 fractures in the Enhanced Characterization of the Repository Block Cross-Drift detailed line survey data set) have likely undergone dilation to accommodate emplacement of the fill material.

Table 2-1. Summary of DOE Fracture Petrogenesis Reclassification				
Data Source		Total Number of Fractures	Cooling-Related (Percent)	Indeterminate (Percent)
Core Slabs		2,022	69.7	30.3
Detailed Line Survey	Large-Scale	1,810	71.1	28.9
	Small-Scale	2,145	48.9	51.1

2.2.2 Lithophysae Analyses

Panel maps based on drift wall photographs from the Enhanced Characterization of the Repository Block Cross-Drift were analyzed by DOE to assess evidence for the presence or absence of seismically induced damage in the Topopah Spring Tuff at Yucca Mountain. Photographs were collected to support lithophysal studies in 2001 and 2002, and fracture and lithophysal studies in 2003 and 2004 (Bechtel SAIC Company, LLC, 2004c, Appendix O). The panel maps (i.e., line drawings or tracings) cover a subset of the photographed area (approximately 50 to 70 percent), and were designed to document the shape, size, and abundance of lithophysae and other features such as spots and lithic clasts (Bechtel SAIC Company, LLC, 2005). Lithophysae shapes include simple, merged, cuspate, and expansion-crack. The simple, merged and expansion-crack shapes are inferred to reflect growth and cavity inflation during welding. While the DOE acknowledges that the cuspate lithophysae are consistent with partial deflation of a cavity that has been cut by a propagating fracture, the DOE suggests that the cuspate shape could also be a variant of the expansion-crack lithophysae. In addition to shape, data on backfilled, or collapsed lithophysae as well as those transected by fractures or shears are documented in an Excel spreadsheet (*PGV Lithop Shapes ECRB.xls*) that is included as part of Appendix D (Bechtel SAIC Company, LLC, 2005).

Based on the lithophysae analyses, the DOE conclude that the majority of lithophysae do not exhibit evidence of deformation because their shapes reflect only cooling-related processes. Out of more than 1,000 measurements, the DOE only recognized seven lithophysae that are transected by fractures and only five lithophysae that are sheared. No lithophysae are reported to be collapsed.

2.3 DOE Ground Motion Calculations and Development of Ground Motion Bound

Sections 6.5 to 6.8, and Appendix C, of Bechtel SAIC Company, LLC (2005) outline the DOE methodology used to develop bounds on horizontal peak ground velocity. This methodology relied on the results of previous ground-motion site-response modeling (Bechtel SAIC Company, LLC, 2004c), which included the variation of peak ground velocity and associated shear strain with depth (from the surface to the waste emplacement level). Using these results, the DOE estimated values of horizontal peak ground velocity necessary to generate a shear strain equal to the threshold value. DOE asserts that a rock that does not contain geologically observable damage could not have experienced seismic ground motion equivalent to the peak ground velocity needed to generate the threshold shear strain. This assertion forms the technical basis for developing the bounded hazard curve.

2.3.1 Ground Motion Calculations

Ground motion results for the Yucca Mountain probabilistic seismic hazard assessment (CRWMS M&O, 1998) are given for a hypothetical reference rock outcrop, referred to as Point A in Figure 1-1. The results did not consider or incorporate the effects of the upper approximately 300 m [984 ft] of tuff on earthquake ground motion. For this reason, DOE performed site-response calculations (Bechtel SAIC Company, LLC, 2004c), using the ground motion calculated at Point A (Figure 1-1) as input, to obtain site-specific hazard curves for the proposed repository (Point B in Figure 1-1).

Inputs to the DOE site-response model are described in detail in CRWMS M&O (1999) and Bechtel SAIC Company, LLC (2004c, 2002a). In addition, DOE used ground motion inputs (control motions) for the site-response calculations based on the results of the Yucca Mountain probabilistic seismic hazard assessment (CRWMS M&O, 1998). These control motions are consistent with ground motion levels predicted at Point A in Figure 1-1. Specifically, for each hazard level (10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, 10^{-7}/yr), and for structural frequency range (1 to 2 Hz and 5 to 10 Hz), three control motions were developed to account for the magnitude-dependence of the site response. The site response calculations also incorporated uncertainties in input material properties, specifically dynamic material properties (shear modulus reduction and damping as a function of shear strain), and velocity profiles. Two basecase curves were developed each for the dynamic material properties and velocity profiles. Variability was incorporated by randomizing the velocity profiles and dynamic material property curves about their basecase. Two wave propagator types (inclined and vertically incident) were also considered.

Results were developed for eight site-response modeling cases, representing combinations of the two structural frequency ranges, two basecase dynamic material property curves (Upper Mean Tuff or Lower Mean Tuff), and two basecase velocity profiles (P1 or P2). For example, suppose the 1–2 Hz structural frequency range, the Upper Mean Tuff material property curve, and P1 basecase velocity profile were selected; each of the three control motions, developed for the 1–2 Hz structural frequency range, was propagated through 60 randomized velocity profiles (for the P1 basecase) and associated dynamic material property curves (for the Upper Mean Tuff basecase). This resulted in 60 curves of horizontal peak ground velocity and shear strain versus depth, for each input control motion. For the three sets of 60 curves, the median peak ground velocity and median shear strain values versus depth were determined. The values of median

peak ground velocity and strains were then averaged for the depth range of 290 to 392 m [951 to 1,286 ft] corresponding to the average depth range of the lower lithophysal unit of the Topopah Spring Tuff. This process was repeated for the two types of wave propagators. These results were then averaged.

A total of eight pairs of shear strain and corresponding horizontal peak ground velocity values were determined for each site response modeling case for the four hazard levels (10^{-4}/yr, 10^{-5}/yr, 10^{-6}/yr, and 10^{-7}/yr). These results were used to linearly interpolate or extrapolate horizontal values of peak ground velocity for target values of shear strain (0.05, 0.10, 0.20, 0.30, 0.40, 0.50 percent).

2.3.2 Development of Probability Distributions for Horizontal Peak Ground Velocity

The probability distribution for shear-strain threshold, developed in Section 6.4.3 of Bechtel SAIC Company, LLC (2005), was used to develop probability distributions for bounding horizontal peak ground velocity for each of the eight site response modeling cases (see Figure 6-8 on page 6-24 of Bechtel SAIC Company, LLC, 2005). For each case, the values of shear strain and corresponding horizontal peak ground velocity are used to convert the shear-strain threshold distribution to one for horizontal peak ground velocity. The results were most sensitive to the dynamic material property curves. Results showed that the distributions fall into two groups depending on whether the Upper Mean Tuff or Lower Mean Tuff set of dynamic property curves were used in the site response modeling. For the Lower Mean Tuff grouping of distributions, shear strains associated with the shear-strain threshold were generated at ground motion levels of about 100 to 230 cm/sec [3.28 to 7.55 ft/sec]. For the Upper Mean Tuff grouping of distributions, ground motions of about 180 to 490 cm/sec [5.91 to 16.1 ft/sec] were needed to generate the shear strains at the threshold level.

2.3.3 Development of Bounded Hazard Curve

The unbounded hazard curve for the waste emplacement level (Point B in Figure 1-1) was determined directly from the results of ground-motion site-response modeling for annual exceedance frequencies of 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}. To obtain a bounded hazard curve, each of the eight bounding horizontal PGV triangular distributions was combined individually with the unbounded hazard curve to produce eight modified mean curves. For each value of horizontal peak ground velocity, the probabilities of the eight modified curves were arithmetically averaged to produce a final modified mean hazard curve (see Figure 6-9 on page 6-26 of Bechtel SAIC Company, LLC, 2005).

3 STAFF REVIEW AND CONCERNS

As discussed in the preceding chapter, the DOE used a multi-disciplinary approach that incorporated geologic and engineering data and models as the basis for the proposed upper bound on horizontal peak ground velocity at Yucca Mountain. Although the application of an inter-disciplinary approach appears to be appropriate, the review demonstrates that the technical basis provided in the DOE report (Bechtel SAIC Company, LLC, 2005) is vulnerable to criticism at several different levels. In this chapter, staff provide a detailed review of the critical points in Bechtel SAIC Company, LLC (2005) and identify a number of significant concerns with the approach used by DOE to develop a bound on horizontal peak ground velocity.

3.1   Effects of Rock Strength on Ground Motion Amplitudes

3.1.1 Theoretical Discussion

An important premise of the DOE technical basis is the assertion that the amplitudes of ground motion are limited by the strength of the materials through which they propagate (Bechtel SAIC Company, LLC, 2005, p. 6-1). A set of seismic ground motions would be large enough to cause mechanical damage if the stress state induced by the motion satisfies the yield criterion for the rock. The yield criterion for a rock (or any solid) defines the stress condition necessary for permanent deformation of the rock, and can be expressed as a mathematical function of stress, F_{yield}. It should be noted that F_{yield} is a function of stress alone (e.g., Desai and Siriwardane, 1984, p. 206; Nielsen, 1984, p. 2).

A stress state that gives a negative value for F_{yield} (i.e., $F_{yield} < 0$) represents a condition that the rock can sustain without undergoing permanent deformation. Stress states for which $F_{yield} = 0$ represent conditions for which permanent deformation of the rock could occur. A stress state that would give a positive value for F_{yield} (i.e., $F_{yield} > 0$) cannot be sustained or transmitted by the rock. The strength or, generally, yield criterion, of a rock (or any solid), therefore, constrains the stress states or magnitudes of stress components that may be supported or transmitted by the rock. The yield criterion, being a function of stress alone, however, does not prescribe any constraints on motion. The magnitudes of particle motion (displacement, velocity, or acceleration) for a solid are determined by the external forces, boundary constraints, material stiffness, and any energy absorption associated with permanent deformation.

Yielding of a rock may cause the particle motions to increase because of reduced stiffness but also may cause a decrease in motion because of energy absorption and reduced force transmission. A net increase or decrease of particle motion (displacement, velocity, or acceleration), therefore, may result from yielding and can be determined from a case-specific analysis. The generalized assumption that the yielding of a rock (or any solid) constrains the magnitude of particle motion, however, may not be technically defensible.

3.1.2 Numerical Experiment

A simple numerical experiment, using the commercial finite-element code ABAQUS®, was performed at CNWRA to examine the effects of rock yielding on ground motions transmitted through a rock. The model geometry used for the experiment consists of a vertical section through an infinite elastic medium broken into two zones by a thin horizontal layer of an

elastic-plastic material with a constant shear strength of 0.75 MPa (Figure 3-1). A sinusoidal shear stress time series was applied near the base of the lower elastic zone (i.e., below the thin weak layer) and shear stress, displacement, velocity, and acceleration were monitored at a point within the upper elastic zone 200 m [696 ft] above the thin weak layer. The amplitude of the input shear stress history was set to 1.0, 2.0, and 3.0 MPa in three test cases. The thin layer yields when the shear stress is 0.75 MPa. The thin layer, therefore, plays the role of a yielding zone (or layer) in the experiment.

The calculated results illustrate that the magnitudes of shear stress and horizontal ground velocity in the upper elastic zone were limited to a maximum of 0.75 MPa and 0.15 m/s, respectively (Figures 3-2 and 3-3). The magnitudes of ground displacement and acceleration in the upper elastic zone, however, were not limited but increased as the magnitude of the input source increased (Figures 3-4 and 3-5). The results illustrate that the shear stress transmitted through the yielding layer is capped at a value equal to the shear strength of the layer as expected. The transmitted velocity also appears to be capped but the displacement and acceleration transmitted through the yielding layer increase as the strength of the source increases.

The experimental setup includes several simplifications that likely have considerable effects on the calculated results: (i) a simple sinusoidal shear wave was used as input instead of a typical ground motion time history; (ii) a single yielding layer that is uniformly thick and perfectly horizontal does not capture the complex subsurface geology at Yucca Mountain; (iii) the strength of the yielding layer is purely cohesive rather than cohesive and frictional, which would be a more realistic representation for rock; (iv) the material surrounding the yielding layer is linear-elastic rather than a more realistic inelastic material; and (v) the zone above the yielding layer is infinite instead of semi-infinite. Such simplifications likely affect ground motion transmission through the yielding layer, such that a generalization of the calculated results would be inappropriate. The results, however, illustrate that amplitudes of ground motion transmitted through the system are not necessarily limited by yielding of the thin layer.

3.2   Pervasive Geologically Observable Damage

An important assumption used to support the technical basis for the DOE proposed cap on horizontal peak ground velocity is that geologically observable damage will occur pervasively in a rock mass that experiences levels of seismic ground motion that correspond with the predicted threshold shear strain (Bechtel SAIC Company, LLC, 2005). DOE does not present objective or quantifiable criteria (e.g., based on natural examples of rock damage produced by actual earthquakes) to distinguish between pervasive damage to rock expected for seismic ground motion at or above the threshold shear strain, and geologic structures that formed from weaker ground motions or even from aseismic (i.e., non-earthquake) processes. There is, for example, no analysis of fracture size and density distributions, that could be applied objectively to an area to assess its ground motion history. The following section discusses several interrelated concerns with the fundamental assumptions that underlie the approach that the DOE used to assert that pervasive geologically observable damage is not present in the lithophysal rock at Yucca Mountain. The fundamental assumptions are that (i) geologic deformation is spatially homogeneous, (ii) geologic deformation is scale-independent, and (iii) rocks are faithful recorders of all deformation processes to which they have been subjected.
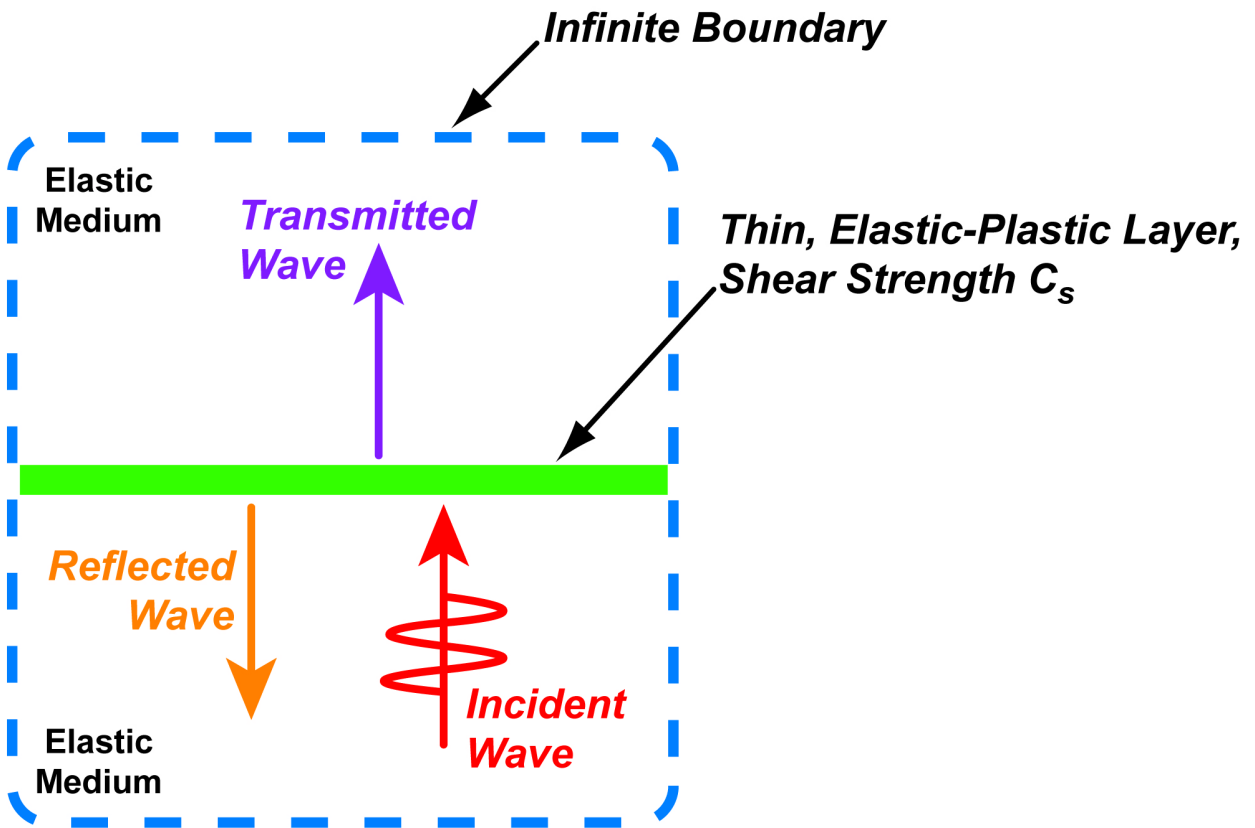
Figure 3-1. Model Geometry Used for Numerical Experiment on Ground-Motion Transmission Through a Relatively Weak Material
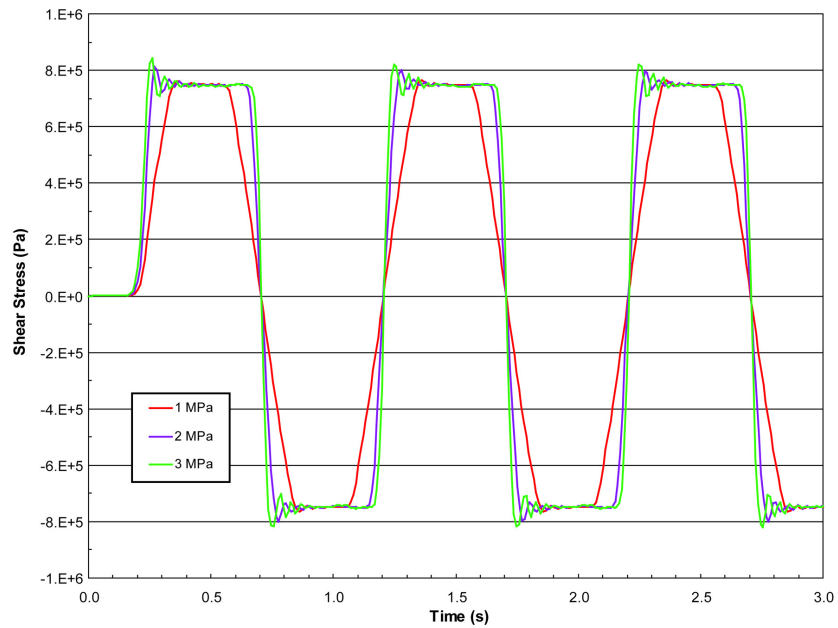
Figure 3-2. Effects of Input Shear-Stress Amplitude on Shear Stresses Transmitted Through a Yielding Thin Layer in an Infinite Medium
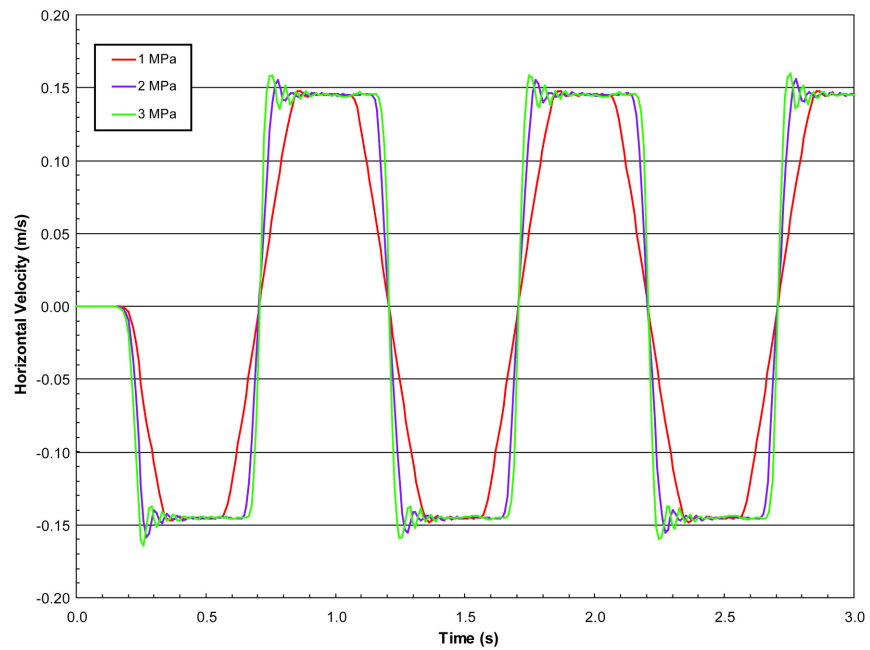
Figure 3-3. Effects of Input Shear-Stress Amplitude on Ground Velocities Transmitted Through a Yielding Thin Layer in an Infinite Medium
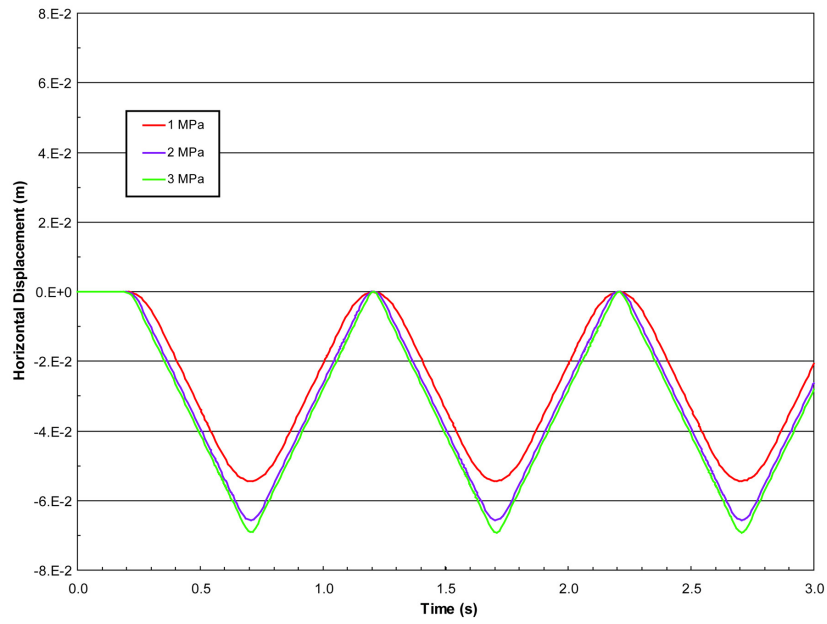
Figure 3-4. Effects of Input Shear-Stress Amplitude on Ground Displacements Transmitted Through a Yielding Thin Layer in an Infinite Medium
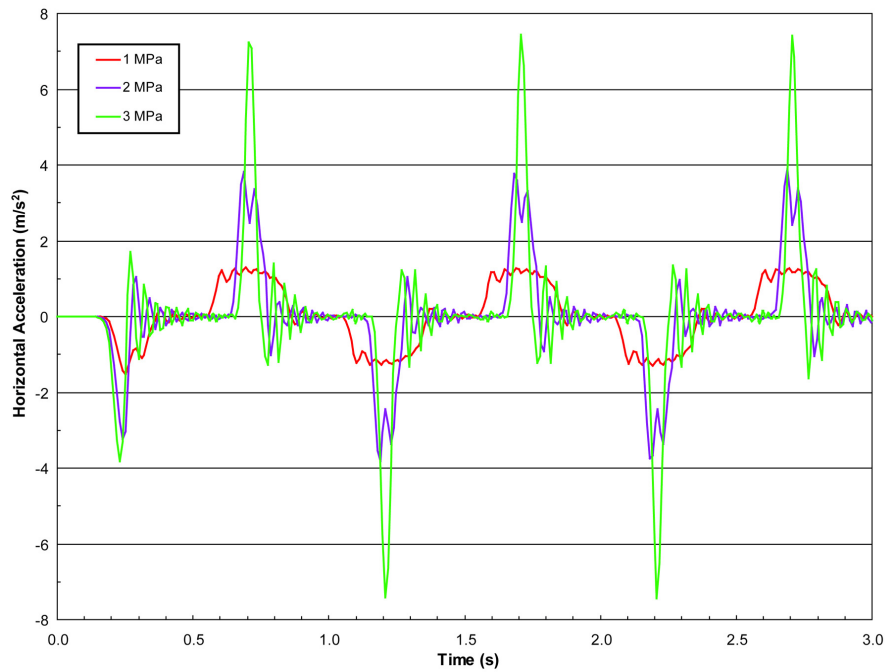
Figure 3-5. Effects of Input Shear-Stress Amplitude on Ground Accelerations Transmitted Through a Yielding Thin Layer in an Infinite Medium

3.2.1 Geologic Deformation Is Spatially Heterogeneous

There are few studies of rock damage resulting from seismic shaking, and these are focused primarily on the damage sustained by tunnels (e.g., AFTES/AFPS Working Group, 2001; Sharma and Judd, 1991; Wang, 1993). Although the previous work does not provide quantitative, observational information concerning deformation distributed through the rock mass, it does emphasize the principle that damage to tunnels during seismic shaking is not homogeneously distributed, but is greatest at or near pre-existing faults and/or zones of high fracture density. Geologic deformation is spatially heterogeneous (i.e., localized) in that the features in a rock that record permanent deformation are not distributed uniformly throughout the rock mass. This is especially true for geologic structures, such as faults and fractures, that result from brittle deformation in the upper crust of the Earth {i.e., depths of less than 10 km [6 mi]}. As a result it is possible that field analyses can lead to an incorrect estimate of the deformation within a particular study area because the selected sample sites do not adequately capture the true nature of the deformation. The situation is further complicated when the study site is underground. Typically, cores can only be recovered successfully from those portions of a borehole where the rock is least deformed (e.g., where the fracture density is low). Likewise, the most deformed rock in a drift is often hidden from further analysis by the need for extra ground support. The result is an inherent bias towards characterizing only the least deformed portions of a rock mass, and therefore leads to underestimation of the total deformation recorded in the rock mass.

Geologic deformation is a complex interaction of processes that can be accommodated by either the formation of a new structure (e.g., fault or fracture) or by the reactivation of an existing structure. Once a geologic structure such as a fault or fracture forms, subsequent deformation is often accommodated by slip or opening along the pre-existing structure (i.e., reactivation) rather than through the formation of a new fault or fracture (e.g., Morris, et al., 1996; Ferrill, et al., 1999, 1998). This is especially true for faults and fractures because the energy necessary to cause slip along an existing fault or fracture surface is generally less than the energy required to form a new fault or fracture surface. This is exemplified by the relatively narrow fault zones at Yucca Mountain that accommodate large displacements between relatively broad fault blocks (Figure 3-6). Consequently, large seismic ground motions may have occurred at Yucca Mountain in the past with much of the motion (and associated strain) accommodated by slip and opening or closing of existing structures such that little or no damage of the rock bounded by these occurred. For example, Sweetkind and Williams-Stroud (1996) and Gray, et al. (2005) document cooling joints with tubular structures at Yucca Mountain that were reactivated with minor displacement and development of foliated clay gouge or fault rock.

3.2.2 Geologic Deformation Is Scale-Dependent

Geologic deformation is also scale dependent. Regional- or repository-scale structural analyses reveal a few large faults (Figure 3-6) at Yucca Mountain such that it might be possible to argue that the site is relatively undeformed. In contrast, structural analyses at the scale of an outcrop or drift document many small faults and fractures (Figures 3-7 and 3-8), from which it is reasonable to conclude that the Yucca Mountain site is moderately (or even highly) deformed. Different assessments of the deformation intensity will occur even for an outcrop-scale analysis because it is possible to select a sample region that appears undeformed (red circles in Figure 3-8) even though a broader view clearly reveals a record of deformation.
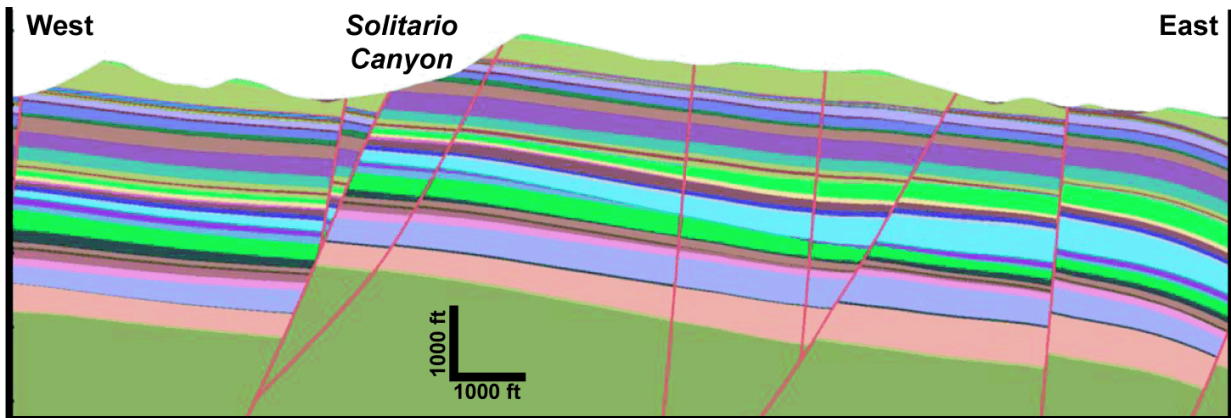
Figure 3-6. Illustration of Fault-Bounded Blocks That Are Characteristic of the Repository-Scale Structural Geometry at Yucca Mountain, Nevada. East-West Cross Section Extracted From the DOE EarthVision Geologic Framework Model (Bechtel SAIC Company, LLC, 2002b). Figure is Modified From Bechtel SAIC Company, LLC (2004d, Figure M–1, p. M–2).
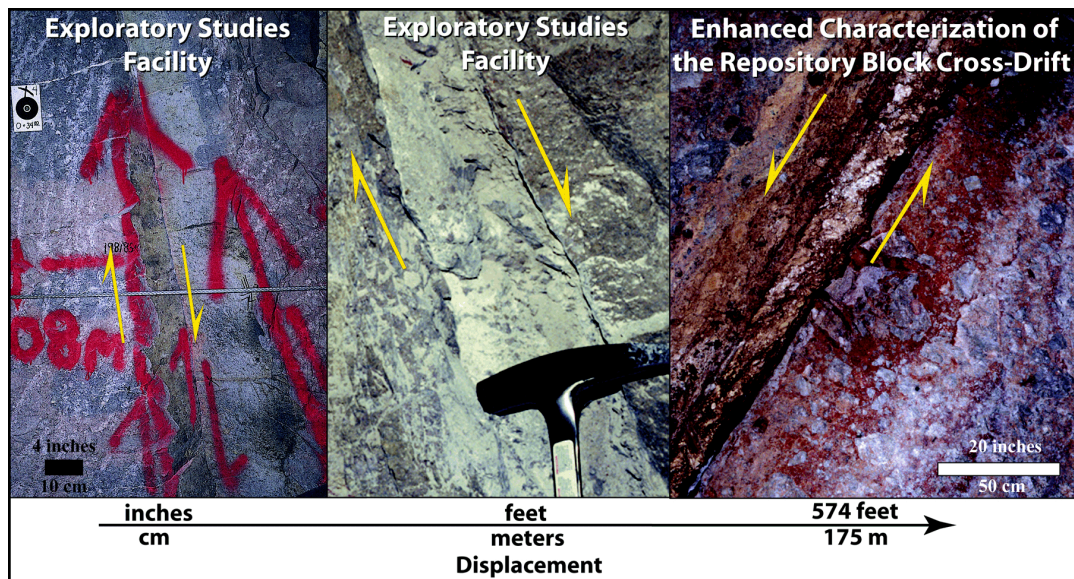
Figure 3-7. Example of Three Faults (Out of More Than 900) Mapped In the Exploratory Studies Facility and the Enhanced Characterization of the Repository Block Cross-Drift, Illustrating a Range of Displacement From a Few Centimeters (Inches) to Hundreds of Meters (Feet). Figure Is Modified From Gray, et al. (2005).
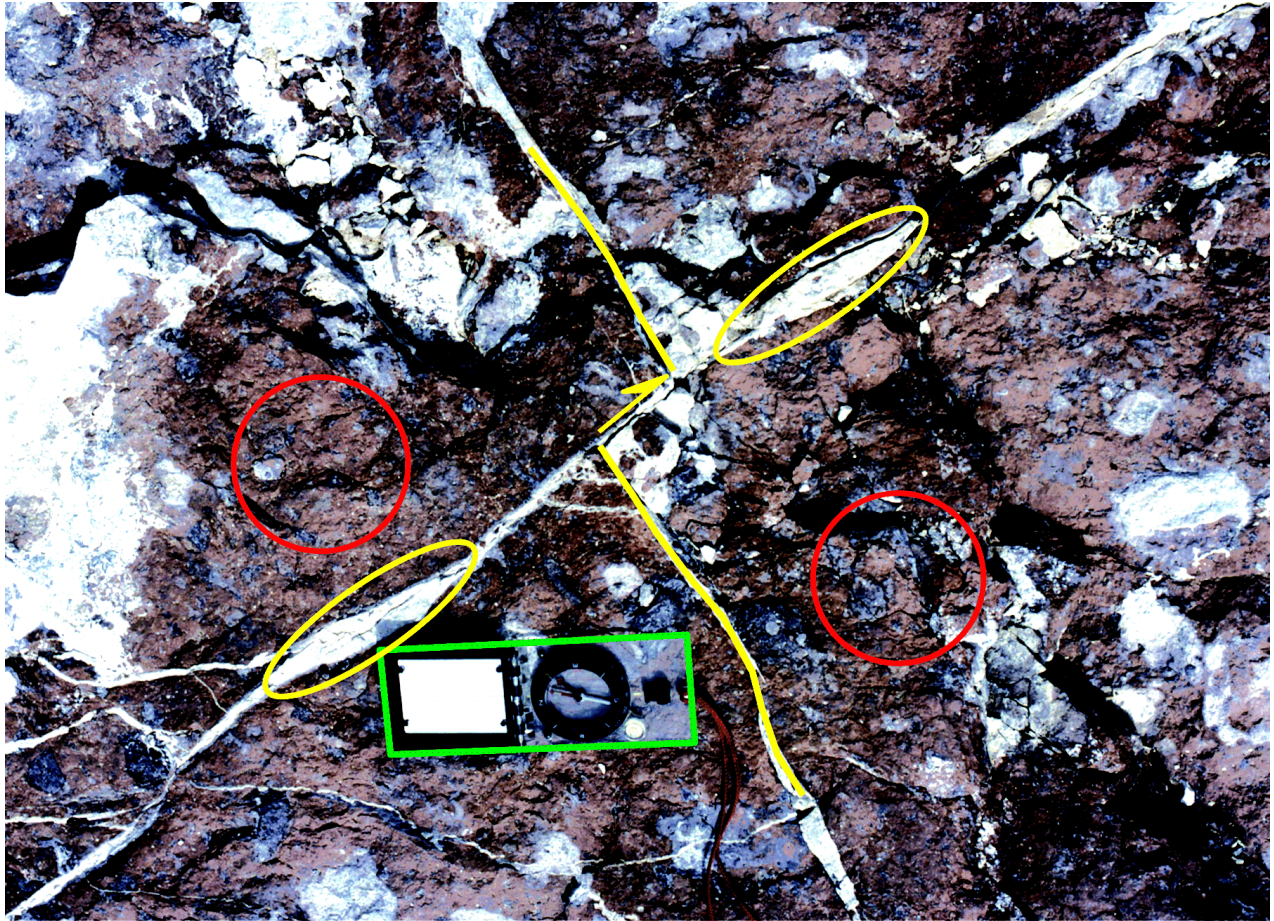
Figure 3-8. Photograph of Mineralized Fractures on Pavement P2001, Fran Ridge. Fracture Running From Bottom Left to Top Right Exhibits Right-Lateral Shear That Displaced the Fracture Highlighted in Yellow. Dilational Jogs (Highlighted by Yellow Ellipses) Along the Slipped Fracture Are Consistent With the Sense and Amount of Displacement Indicated by the Offset Fracture. Rock Between Fractures (Highlighted by Red Circles) Is Undeformed. Compass {Outlined in Green, and Approximately 18 cm [7 in] Long} for Scale.

While the DOE analysis is based on spatially and stratigraphically distributed samples from Yucca Mountain, it does not consider the entire wealth of available fault and fracture data. The published literature documents dozens of faults and tens of thousands of fractures of cooling and tectonic origin that have been measured in the volcanic strata mapped at Yucca Mountain (e.g., Dunne, et al., 2003; Ferrill and Morris, 2001; Ferrill, et al., 1999; Gray, et al., 2005; Morris, et al., 2004; Nieder-Westermann, 2000; Scott, 1990; Smart, et al., 2006; Throckmorton and Verbeek, 1995). The variety of fracture orientation sets present in the rock mass provides a range of opportunities for fracture dilation or slip without requiring new fracture formation.

The DOE conclusion that Yucca Mountain has not experienced ground motions that correlate with the threshold shear strain calculated in Bechtel SAIC Company, LLC (2005) is based on the interpretation that Yucca Mountain does not show evidence of widespread geologically observable damage. Because this term is not unambiguously defined, and because rocks at Yucca Mountain are clearly faulted, fractured, and dilated at all scales (e.g., Figure 3-9), the DOE argument is vulnerable to the reverse interpretation—that ground motions that correlate with the threshold shear strain may have been experienced in the last 12.8 million years.

3.2.3 Geologic Deformation Is Incompletely Captured in Rock Record

In Section 6.3 of Bechtel SAIC Company, LLC (2005), it is assumed that the features in a rock represent the major processes that have occurred throughout its geologic history and that these features can be used to reconstruct the sequential development of the rock-forming processes. However, geologic structures represent an incomplete record of the processes that have occurred. Some processes leave behind no record, and some deformation mechanisms such as reactivation of a pre-existing fracture by opening or closing may partly or completely overprint early-formed features. Evidence may be subtle, such as material that sifted or washed into an open fracture during an ephemeral dilation event. Geologic events can often only be dated in a relative sense. While it is sometimes possible to make reasonable interpretations of the geologic history, the result is non-unique and alternative conceptual models may be equally valid.

3.3   Additional Staff Concerns

3.3.1 Lack of Data Support for Threshold Shear Strain

The values of strain provided by DOE as representing the shear strain needed to cause mechanical damage of lithophysal rock (Bechtel SAIC Company, LLC, 2005, p. 6-13 to 6-18) were based on calculated information that has not been verified against any measured data. Strain data for lithophysal rocks available to DOE were used only to determine values of rock stiffness that were input into a calculation model. The results of the calculation were not verified against any empirical strain data. The DOE information also included calculations performed using micromechanical models of lithophysal rock, but characteristics of the model that are known to affect the magnitudes of calculated strain were not calibrated.
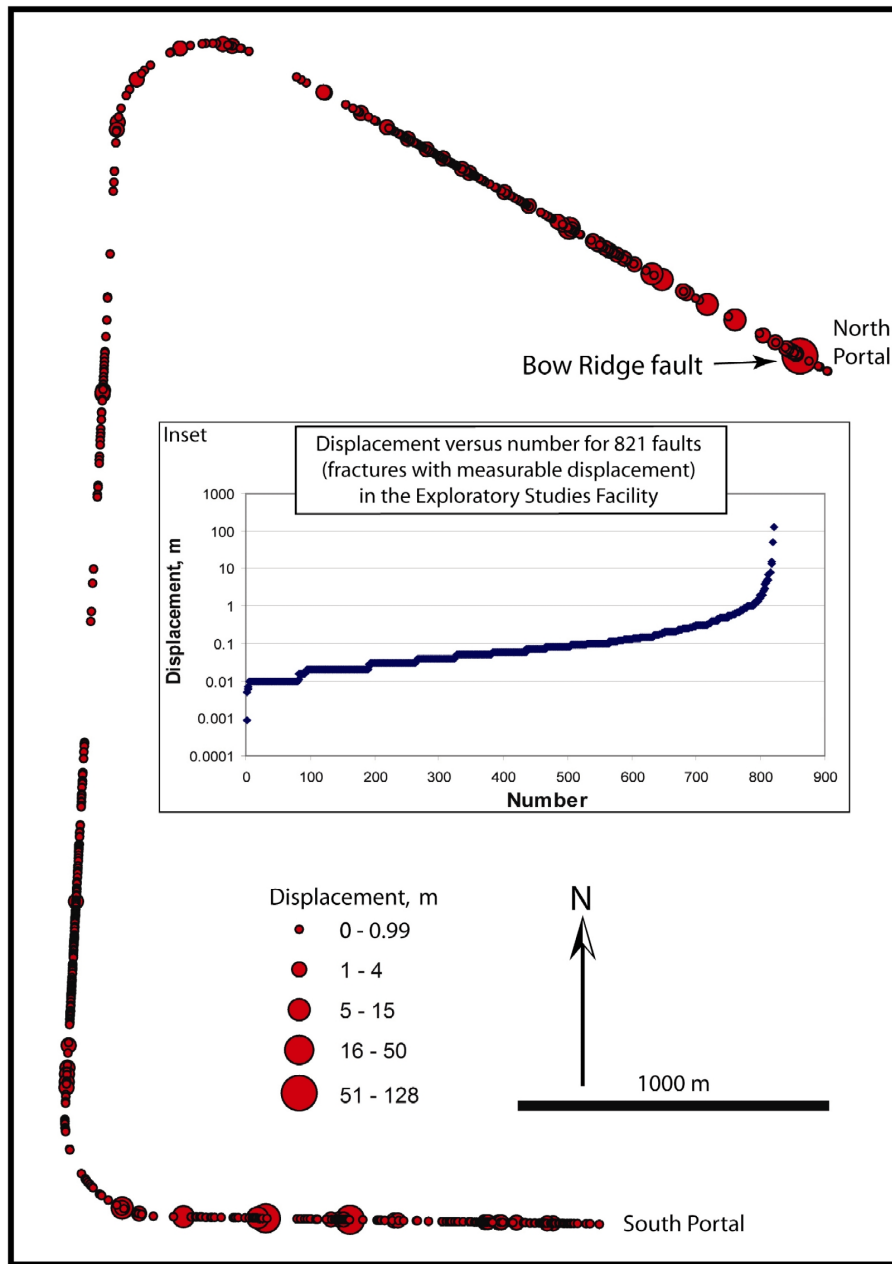
Figure 3-9. Map of 821 Fault Locations Within the Exploratory Studies Facility. Symbols Are Sized According to Recorded Displacement. Inset Is a Graph of Displacement Versus Number Ordered by Displacement Magnitude. Data Are From Exploratory Studies Facility Detailed Line Surveys, Data Tracking Numbers: GS960908314224.008, GS960908314224.010, GS960908314224.011, GS960908314224.014, GS960908314224.018, GS960908314224.020, GS970808314224.003, GS970808314224.006, GS970808314224.008, GS970808314224.010, GS970808314224.012, GS970808314224.014, and GS970808314224.020 Through GS970808314224.028.

3.3.1.1   Calculations Based on Linear Elastic Modeling

Empirical data from rock failure tests were not used by DOE to determine the threshold shear strain. DOE has previously performed laboratory compression testing of the lithophysal rock that included measurements of axial stress, and axial and circumferential strains from cylindrical specimens (e.g., Bechtel SAIC Company, LLC, 2004d, Appendix E). DOE stated that strain measured from laboratory compression testing "corresponds to a certain uniaxial stress path from an initial, unstressed state to the damage state," therefore, cannot be used to represent the threshold shear strain (Bechtel SAIC Company, LLC, 2005, p. B-5). Even if the stress and strain data obtained from the tests are not appropriate for determining the threshold shear strain, the tests at least indicate that appropriate testing with appropriate stress and strain measurements could be performed. The measured strain, in fact, could be used to estimate the threshold shear strain, perhaps with a calculated correction to account for the initial unloading of the specimens from their *in situ* state to a stress-free state prior to compressive loading in the laboratory. DOE instead calculated its threshold shear strain using a set of equations based on linear elasticity and the Mohr-Coulomb strength criterion. The laboratory data from compression testing of lithophysal rock (Bechtel SAIC Company, LLC, 2005, Table B-1, p. B-10) were used only to determine the values of Young's modulus and unconfined compressive strength, which were used as input for the calculation. The values of other input parameters needed for the calculation (e.g., Poisson's ratio, friction angle, and *in situ* horizontal stress) either were assumed or calculated from a numerical model (Bechtel SAIC Company, LLC, 2005, p. B-8).

3.3.1.2   Calculations Based on Micromechanical Modeling

In addition to the linear-elastic calculations reviewed previously, DOE performed other calculations using numerical models of lithophysal rock implemented in PFC2D or UDEC (Bechtel SAIC Company, LLC, 2005, p. 6-10) to evaluate the effects of lithophysal porosity on threshold shear strain. In the two codes, lithophysal rock is modeled as an assemblage of bonded particles with a distribution of void spaces representing the lithophysal openings. Values of micromechanical parameters (e.g., particle contact shear and tensile strength, and shear and normal stiffness) needed for the model were evaluated by calibrating the elastic stiffness and compressive strength of the model against measured elastic stiffness and unconfined compressive strength. The tensile strength and dilation behavior (i.e., ratio of lateral to axial strains) of the model and its stress-strain behavior under confined compression were not calibrated and may have significant effects on the calculated results. DOE indicated the tensile and dilation behavior and stress-strain response under confined compression calculated using the models are generally reasonable based on previous experience. Although such qualitative judgement may be sufficient to indicate the modeling approach may be theoretically valid, a quantitative calibration of a model against important stress-strain measures of rock behavior is necessary in order to rely on the model for a quantitative characterization of rock behavior.

Independent analysis (Cho, et al., 2004), for example, indicate the basic formulation of a PFC2D micromechanical model (i.e., an assemblage of bonded discs calibrated against the elastic stiffness and unconfined compressive strength of the modeled rock) likely overestimates the tensile strength of rock and underestimates the potential dilation strain. Cho, et al. (2004) suggested model changes (e.g., use of assemblage of particle groups instead of individual particles) to improve the model response regarding tensile resistance and dilation straining. DOE appears to have used the basic formulation in its calculation, which raises a concern regarding

the calculated values of threshold shear strain. Moreover, DOE did not provide any strain data to serve as a verification of the calculated information.

3.3.2 One-Dimensional Equivalent-Linear Site Response Analyses

There are three concerns with the DOE site response model and inputs. First, nonlinear behavior is treated in an approximate (equivalent-linear) fashion. Second, the one-dimensional model may not account for important two- and three-dimensional effects (e.g., effects of topography, and faulted or dipping layers). Third, the dynamic material property data used for the one-dimensional equivalent-linear analyses are based on experimental data that were collected under conditions that are not representative of low probability seismic events at the waste emplacement level at Yucca Mountain.

Ground-motion site-response modeling results from previous one-dimensional equivalent-linear simulations (Bechtel SAIC Company, LLC, 2004c) were used to correlate shear strain and peak ground velocity, and thus estimate the peak ground velocity needed to generate the threshold shear strain. The adequacy of this correlation is dependent on the limitations of the site response model and the geotechnical inputs.

3.3.2.1   Limitations Associated With the DOE Site Response Model

Many studies have shown that soil and rock may behave nonlinearly (e.g., Beresnev, et al., 1998; Borja, et al., 2000; Johnson and Rasolofosaon, 1996; Johnson, et al., 1996; Yu, et al., 1993), particularly when subjected to strong ground motions. Kramer and Paulsen (2004) note that nonlinear models tend to be necessary for analyses where large strains or displacements are expected. Makadisi and Wang (2004) suggest that for sites located close to major active faults and subjected to strong ground shaking, site response can be more appropriately estimated using fully nonlinear procedures.

The equivalent-linear method approximates nonlinear site response by iteractively adjusting the stiffness and damping parameters of the soil or rock layers until they are made compatible with the strain levels induced by the earthquake loading (Kramer, 1996; Lo Presti, et al., 2006). A major limitation of the equivalent-linear method is that the strain-compatible material properties remain constant throughout the duration of the earthquake, regardless of whether the strains at a particular time are large or small (Kramer, 1996). As such, the method may overestimate the seismic response due to the coincidence of a strong component of the input motion with one of the natural frequencies of the equivalent-linear deposit (Kramer, 1996; Xu, et al., 2003). In reality, the stiffness of an actual nonlinear material changes over the duration of a large earthquake and these calculated high amplifications levels will not develop in the field (Kramer, 1996). Yu, et al. (1993) show that nonlinear response can be separated into three frequency bands. In the lowest frequency range, spectral amplitudes are not affected by the nonlinearity. In the central band, the spectral amplitudes are decreased. Their results also predicted a transition frequency above which amplification factors increase relative to the linear response. In addition, the equivalent-linear method cannot be used to model permanent displacements because the shear strains return to zero after the earthquake loading is complete (Borja, et al., 2002; Kramer and Paulsen, 2004; Xu, et al., 2003). Comparisons of equivalent-linear and fully nonlinear codes have shown the shear strain time histories, including maximum predicted shear strains, may also differ significantly (e.g., Borja, et al., 2002; Lo Presti, et al., 2006).

The one-dimensional approach is also limited because the effects of topography, and faulted and dipping layers cannot be accounted for (Kramer and Paulsen, 2004). Many recent studies have shown that two- and three-dimensional analyses may be required to fully capture complexities in the subsurface such as dipping layers and sedimentary basin effects (e.g., Bardet, et al., 1997, 1992; Bielak, et al., 1999; Frankel, 1993; Hartzell, et al., 1996; Zhang and Papageorgiou, 1996; Xu, et al., 2003). For example, Bardet, et al. (1992) reported that two-dimensional analyses predicted larger accelerations than one-dimensional analyses and suggested that one-dimensional site-response analyses used in engineering practice may not necessarily be conservative. Given the complex site geometry at Yucca Mountain (i.e., faulted and dipping tuff units, and topography), multi-dimensional effects may significantly influence the predicted levels of ground motion at the site.

3.3.2.2   Limitations Associated With the DOE Site Response Inputs

The staff review of the limitations associated with the DOE site response inputs focused on the dynamic material property data, because calculated peak ground velocity (Bechtel SAIC Company, LLC, 2004c) was extremely sensitive to the selection of either the Upper Mean Tuff or Lower Mean Tuff curves, which are based on this dynamic material property data. Curves were developed for both shear modulus reduction, and damping as a function of shear strain. Larger peak ground velocities were calculated when the Upper Mean Tuff curves were used. The probability distributions, developed for horizontal peak ground velocity in Bechtel SAIC Company, LLC (2005), fall into two groups depending on whether the Upper Mean Tuff or Lower Mean Tuff set of dynamic property curves were used in the site response modeling. For the Lower Mean Tuff grouping of distributions, shear strains associated with the shear-strain threshold were generated at ground motion levels of about 100 to 230 cm/sec [3.28 to 7.55 ft/sec]. For the Upper Mean Tuff grouping of distributions, ground motions of about 180 to 490 cm/sec [5.91 to 16.1 ft/sec] were needed to generate the shear strain threshold level of shear strains.

The development of the Upper Mean Tuff and Lower Mean Tuff dynamic property curves (detailed in Bechtel SAIC Company, LLC, 2004c) was based on dynamic laboratory testing of tuff specimens obtained from boreholes from the area previously referred to as the Waste Handling Building site (a total of 24 specimens), and the North Portal Area of the Exploratory Studies Facility (a total of 5 specimens). The resonant column and torsional shear testing performed on the tuff specimens is described in Bechtel SAIC Company, LLC (2002a), and the development of the Upper Mean Tuff and Lower Mean Tuff dynamic property curves is detailed in Bechtel SAIC Company, LLC (2004c). The tested tuff specimens included units of the Tiva Canyon Tuff. However, the repository host horizon consists of the lower units of the Topopah Spring Tuff. Dynamic test data are not available for any of the Topopah Spring Tuff units, nor for some of the overlying bedded tuff units. Thus, there is large uncertainty regarding the behavior of the Topopah Spring Tuff.

Bechtel SAIC Company, LLC (2002a) notes that there is also a high degree of uncertainty regarding the dynamic behavior of tuff units at high strain levels (i.e., beyond 0.1 percent). For shear strains beyond this level, the Electric Power Research Institute report (1993) was used by DOE to guide the extrapolation of the Upper Mean Tuff and Lower Mean Tuff curves beyond the range of available data. Bechtel SAIC Company, LLC (2002a) notes that the dynamic laboratory measurements of material properties were limited to strains of about 0.1 percent in this study because the emphasis was placed on the preclosure seismic design hazard levels defined at annual exceedance probabilities of 10^{-3} and 10^{-4}. In addition, Bechtel SAIC Company, LLC

(2002a) documents several of the samples failing at strain levels of around 0.1 percent. Furthermore, not all of the samples are tested to strain levels of 0.1 percent. Many samples were only tested to strain levels less than 0.01 percent (and even 0.001 percent). However, no explanation is provided in Bechtel SAIC Company, LLC (2002a) as to whether strain level limitation was a result of sample failure. The high degree of uncertainty regarding the dynamic behavior of the tuff units at shear strain levels beyond 0.1 percent is important because in Bechtel SAIC Company, LLC (2005), values of horizontal values of peak ground velocity were linearly interpolated or extrapolated for target values of shear strain up to 0.5 percent.

3.3.3 Staff Review of DOE Use of Fracture and Lithophysae Observations

As discussed in Section 2.2 of this review, one component of the technical basis for the proposed cap on horizontal peak ground velocity is the assertion by the DOE that the lithophysal rocks of the Topopah Spring Tuff at Yucca Mountain do not show evidence of geologically observable damage that would be expected from extreme seismic shaking. In this section of the review, the authors detail their concerns that the evidence presented by the DOE is insufficient to justify the conclusion that the lithophysal rock at Yucca Mountain does not exhibit geologically observable damage.

3.3.3.1   Fracture Petrogenesis

The re-evaluation of fracture petrogenesis described in Bechtel SAIC Company, LLC (2005), represents a major shift in interpretation when compared to the nearly two decades of published research on the structural geology and tectonics of Yucca Mountain (e.g., Barton, et al., 1993; Dunne, et al., 2003; Gray, et al., 2005; Mongano, et al., 1999; Morris, et al., 2004; Nieder-Westermann, 2000; Scott, 1990; Sweetkind and Williams-Stroud, 1996; Sweetkind, et al., 1995a,b; Throckmorton and Verbeek, 1995). While researchers have recognized the presence of cooling-related fractures at Yucca Mountain, only one previous study has suggested that the great preponderance of fractures are related to cooling (Buesch, et al., 1999).

The fracture hierarchy used in Bechtel SAIC Company, LLC (2005) is composed of three cooling-related categories (i.e., Types 1, 1+, and 2) and an indeterminate category that the DOE suggests may also be composed of late cooling fractures. As established, this hierarchy is not objective because it presumes a priori that all fractures are cooling-related and does not allow for the possibility of tectonically induced fractures. In addition, the reclassification does not account for the well documented geometric relationships between fractures (Dunne, et al., 2003; Mongano, et al., 1999; Morris, et al., 2004; Nieder-Westermann, 2000; Smart, et al., 2006). The observation that fracture orientations are not random, but fall into three or four repeatable sets (e.g., Smart, et al., 2006; Throckmorton and Verbeek, 1995) is inconsistent with the DOE interpretation that all fractures formed by cooling-related processes alone. As discussed by Dunne, et al. (2003), the presence of well-defined cooling fracture orientation sets requires an additional stress field control (e.g., fault slip, differential compaction) to orient the fracture sets. Furthermore, the reclassification does not adequately consider the documented occurrence of faults at various scales at Yucca Mountain (Figure 3-7) as well as fractures with demonstrable slip or dilation (Figure 3-8).

As described in Section 2.2.1 of this review, the re-analysis of fracture petrogenesis is based primarily on the recorded mineral fill, even though it is acknowledged in Bechtel SAIC Company, LLC, (2005, p. A-7) that the original collection of the fracture data was focused on geometric

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characteristics such as orientation, spacing, and trace length. The re-analysis is also flawed in that an arbitrary or selective application of the recorded fill data was used. For example, if a fracture entry included any mention of a vapor phase mineral, then that fracture was assigned to the cooling-related category even if the original entry also indicated that the fracture had measurable slip or was filled with fault rock (both indicators of tectonic activity). Based on the DOE fracture data, it appears that some fractures that formed as cooling joints were later reactivated, experiencing slip or dilation, in response to tectonic activity (e.g., Gray, et al., 2005, Section 2.4). As part of the staff evaluation, the spreadsheets (*PGV ECRB DLS Frac-Fill.xls* and *PGV SSF DLS Frac-Fill.xls*) included in Appendix D of Bechtel SAIC Company, LLC (2005) were examined. A revision of the DOE reclassification was performed whereby fractures with recorded slip or fill indicative of slip (e.g., broken rock) were moved to the indeterminate category (Table 3-1). Comparison of Tables 2-1 and 3-1 shows that a different breakdown is obtained if all the information in the original fracture data files is considered.

Table 3-1. Revised Fracture Petrogenesis Reclassification				
Data Source		Total Number of Fractures	Cooling-Related (Percent)	Indeterminate (Percent)
Detailed Line Survey	Large-Scale	1,810	59.7	40.3
	Small-Scale	2,145	41.5	58.5

It should be recognized that simply reclassifying fractures as cooling or non-seismic in origin does not remove their ability to accommodate strain. Pre-existing fractures, regardless of origin, will slip, dilate, and accommodate vibratory motion.

3.3.3.2   Lithophysae Analyses

As discussed in Section 2.2.2 of this review, the approach of using lithophysae shape as an indicator of strain or deformation in rock is not an established technique in structural geology. While such an approach to strain analysis could be valid, there is insufficient information in Bechtel SAIC Company, LLC (2005) to support a technically defensible basis for the method. Consequently, the authors conclude that the interpretation by the DOE that the lithophysal tuff at Yucca Mountain is undamaged based upon examination of lithophysae shape is also not technically defensible.

In Bechtel SAIC Company, LLC (2005), the DOE asserts that the lithophysae analyses document that the lithophysal rocks are not characterized by abundant inter-lithophysal fractures. Other DOE documents, however, contradict this claim. According to the Subsurface Geotechnical Parameters report (Bechtel SAIC Company, LLC, 2003, pp. 8–185), short fractures coupled with lithophysae govern stability and the Topopah Spring Tuff lower lithophysal zone has abundant inter-lithophysal fracturing. Figure 8-79b in Bechtel SAIC Company, LLC (2003) shows the intensive fracturing that exists between lithophysae in the upper portion of the lower lithophysal zone. One of the photographs of a core slab from the upper lithophysal zone of the Topopah Spring Tuff (Bechtel SAIC Company, LLC, 2005, Figure A1-5a, p. A-13) that is presented as evidence of the lack of inter-lithophysal fracturing clearly shows an example of a fracture intersecting a lithophysal cavity with a jog that indicates offset or displacement of the fracture after it formed. Indeed, Figure A1-5a in Bechtel SAIC Company, LLC (2005) is remarkably similar in its deformation characteristics to Figure 6-4, in that same report, which documents

inter-lithophysal cracking in a numerically simulated uniaxial compression test. Thus, the information is insufficient to support the DOE assertion that the lithophysal rocks at Yucca Mountain are undamaged.

4 DOE-FUNDED CURRENT AND FUTURE RESEARCH TO BOUND SEISMIC GROUND MOTION

The Yucca Mountain repository site is located in a seismically active region of the United States. Federal regulations require that preclosure safety assessments and postclosure performance assessment calculations include the effects of the range of credible earthquakes. When the probabilistic seismic hazard assessment was conducted in the late 1990's, the expert panel did not fully consider the need to develop a complete range of credible seismic ground motions for the Yucca Mountain site, including consideration of low probability seismic events. The subsequent extrapolation of the hazard curves by DOE to low annual exceedance probabilities has led to predictions of peak ground velocity that most scientists and engineers consider physically unrealistic. Geologic and engineering data on the quantitative effects of large ground motions on rock mass deformation is limited.

Recently, research has been undertaken in both the United States and Europe (e.g., Abrahamson, et al., 2002) to address the problem of defining the upper limits on earthquake ground motion. This chapter describes some of these continuing research efforts that will contribute to the development of a credible ground motion bound. The focus is on the research that is being performed under the Science and Technology Program of the DOE Office of Civilian Radioactive Waste Management focused on researching physical limits to ground motion in the context of Yucca Mountain, Nevada.

The subject of bounding extreme ground motions is discussed extensively in Bommer, et al. (2004) and Strasser, et al. (2004). Both papers provide an in depth discussion of possible channels of research that could be explored in the quest to define maximum possible ground motions. Bommer, et al. (2004) note that the maximum ground motions that can be experienced at the ground surface are controlled by three factors: the most intense seismic radiation that can emanate from the source of the earthquake; the interaction of radiation from different parts of the source and from different travel paths; and the limits on the strongest motion that can be transmitted to the surface by shallow geologic materials.

Andrews (2005, 2004) presents the results of nonelastic two-dimensional dynamic calculations in which the material outside the slip zones is subject to a Coulomb yield criterion. It was found that energy loss in the damage zone, outside the slip zone, increases fracture energy and limits particle velocity at the source. These types of calculations have, in the past, assumed an elastic medium. For example, Day (1982a,b) made the approximation that faulting is confined to a single plane and that the rock mass continuum is linearly elastic everywhere outside that plane.

Bommer, et al. (2004) discuss several possibilities to account for the influence of the strength of surface materials on the maximum surface ground motion including running site-response analyses with increasing amplitudes of the input bedrock motion. They note that this type of analysis requires a genuinely nonlinear algorithm and that equivalent-linear models are of limited use.

A special session at the 2003 Seismological Society of America Annual Meeting was dedicated to "PSHA at Low Probabilities, the Ergodic Assumption, Precarious Rocks, and Shattered Rocks." The special session considered possible statistical modifications of probabilistic seismic hazard assessment, possible physical bases for truncating statistical distributions, and how

constraints from various geologic and geomorphic observations (e.g., precarious rocks and shattered rocks) might be introduced into probabilistic seismic hazard assessment (Brune, 2003).

In September, 2003, the Science and Technology Program of the DOE Office of Civilian Radioactive Waste Management convened the Committee on Extreme Ground Motions at Yucca Mountain. The purpose of this committee was to investigate how these extreme ground motions were predicted and how they might be bounded. In August 2004, the committee held the workshop on extreme ground motions[1]. At this workshop, the committee recommended three research categories: physical limits, unexceeded values, and frequency of occurrence. Physical limits refer to values above which ground motions cannot occur. Unexceeded values refer to ground motion levels that have not occurred in a certain interval of time. Frequencies of occurrence refer to frequency of occurrence of various parameters that measure or control ground motion (e.g., frequency of occurrence of kilobar stress drops). The committee noted that physical limits, if they can be quantified in defensible ways, are the most direct and definitive way of bounding extreme ground motions. The committee recommended that research on the physical limits of ground motion be conducted in two specific areas: (i) nonlinear effects due to rock mass (i.e., nonlinear response of site-specific rock units at Yucca Mountain); and (ii) nonlinear effects at the source resulting from rock-mass damage in the source region.

The workshop on Physical Limits to Earthquake Ground Motion in Rock was held in September 2005[2], in response to the committee's research recommendations on physical limits. The objectives of the workshop were: (i) to convene the broad community of earthquake scientists to identify and discuss physical limits to ground motion either at the source or along the path to the earth's surface; and (ii) to elicit ideas from participants that would contribute to the development of a comprehensive 4-year work plan.

This 4-year work plan (referred to as the Extreme Ground Motions Research Plan) is separated into two tasks. The first task is focused on defining physical limits due to wave propagation, and the second task is aimed at studying limits on ground motion associated with the earthquake source. Both tasks are being performed in the context of the Yucca Mountain site. Researchers from the Southern California Earthquake Center, the Pacific Earthquake Engineering Research Center, and the U.S. Geological Survey are being funded for a period of 4 years to conduct this research, which is intended to be presented in a format appropriate for use in a future probabilistic seismic hazard analysis.

Examples of contributing areas of research include: (i) fault zone geology studies; (ii) laboratory rock mechanics; (iii) fracture mechanics; (iv) rupture dynamics and kinematics; (v) wave propagation; (vi) nonlinear wave propagation modeling, including one-, two- and three-dimensional analyses; (vii) dynamic rupture modeling, including nonelastic response; (viii) fault zone geology research, including rock damage observations; and (ix) laboratory rock mechanics, including mechanisms for near complete stress drop.

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[1]The proceedings of the 2004 workshop (including the research recommendations) were documented in a report (The Workshop on Extreme Ground Motions at Yucca Mountain), which was approved by the Science and Technology Program in May 2005.

[2]A summary of the 2005 workshop is documented in the report "Workshop on Physical Limits to Earthquake Ground Motion in Rock."

Future attempts at defining an upper bound to horizontal peak ground velocity for Yucca Mountain that are directed at studies of the mechanics of earthquake processes could add physical realism. Such research may also lead to objective measures for assessing peak ground velocities that are currently lacking. Because the original DOE probabilistic seismic hazard analysis was developed through an expert elicitation process, DOE also could update the elicitation to consider new information relevant to understanding the physical processes associated with large motion, low probability earthquakes in the vicinity of Yucca Mountain, Nevada.

5 SUMMARY

In summary, the authors of this report have identified a number of significant concerns with the technical basis used by the DOE to support its proposed cap on horizontal peak ground velocity at Yucca Mountain documented in Bechtel SAIC Company, LLC (2005). The DOE technical basis is predicated on two fundamental assumptions.

In the first assumption, the DOE asserts that the amplitude of ground motion is limited by the strength of the propagating medium and that this strength is equivalent to the shear strength at the elastic limit (Bechtel SAIC Company, LLC, 2005). The strength of a solid, however, does not necessarily constrain the magnitude of particle motion. Specifically, the yielding of a solid may cause the magnitude of motion to increase because of reduced stiffness but also may cause a decrease in motion because of energy absorption. A net increase or decrease of ground motion, therefore, may result from yielding and must be determined from case-specific analyses. The authors conclude that this assumption may be incorrect and does not support the proposed cap on horizontal peak ground velocity.

In the second assumption, the DOE asserts that geologically observable damage will occur pervasively in a rock mass that experiences levels of ground motion (and shear strain) that are associated with low-probability seismic events (Bechtel SAIC Company, LLC, 2005). No objective criteria are presented to distinguish between damage expected for extreme seismic ground motion, and that produced by weaker seismic or aseismic events. While the DOE asserts that pervasive geologically observable damage is absent from Yucca Mountain, this conclusion is based on analyses that do not consider the available geologic data that document the presence of hundreds of faults and tens of thousands of fractures produced by both cooling-related and tectonic processes. Further, geologic deformation is often accommodated through the reactivation of pre-existing faults or fractures rather than by the formation of new features, which is not considered in the technical basis presented by the DOE. Bechtel SAIC Company, LLC (2005) does not develop quantitative and objective criteria to assess the state of rock mass damage that might result from seismic ground motion. The assertion that pervasive geologically observable damage is absent from Yucca Mountain is undermined by the lack of objective criteria by which to assess rock mass damage.

Finally, future attempts at defining an upper bound to horizontal peak ground velocity that are directed at studies of the mechanics of earthquake processes such as those developed at the 2005 Workshop on Physical Limits to Earthquake Ground Motion in Rock could add physical realism and may overcome current limitations in the DOE approach for assessing peak ground velocities for Yucca Mountain. Because the original DOE seismic hazard analysis was developed through an expert elicitation process, DOE also could update the elicitation to consider new information relevant to understanding the physical processes associated with large motion, low probability earthquakes in the vicinity of Yucca Mountain, Nevada.

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